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Tooling for production of the Green Fiber Bottle

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Abstract

Ever since the invention of plastics, packaging has become extremely cheap and efficient. In recent times, the demand for more ecological packaging is increasing leading back to the roots of using naturally available resources, which are biodegradable. The manufacturing process of the Green Fiber Bottle (GFB) is based on moulding of wood fibers. The process is still at the research stage and not commercialized. Tooling is the most critical element in moulding and should be adapted to quick water removal techniques, such as Impulse Drying Technology. In this work, functional requirements for the development of a robust tooling solution are identified. Tooling alternatives are investigated and compared with the capacity to enable water removal. Characterization and assessment of porous tool materials using computed tomography are also outlined and discussed.

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Keywords: Biodegradable packaging; Sustainable manufacturing; Tooling process chains; Porous tools

1. Introduction

The field of packaging products is very old and important field, almost tracing back to the start of human evolution. In the modern times, the demand for better packaging have been an ever growing industry, due to the increased demand for exotic and easily perishable goods [1]. Its development during the human history, has made it more efficient and sophisticated, using different materials and adding new functions along its history. Ever since the invention of plastics, packaging have become extremely cheap and efficient. Plastics, in general not being biodegradable, have a heavy impact on the ecological system, both in creation and disposal [2]. In recent times the demand for more ecological packaging have been ever growing, leading back to the roots of using naturally available resources that are easily biodegradable. Therefore, the production of paper packaging has appeared as a viable solution to this problem. In order to replace plastics, moulded paper products are being developed, due to their moulding capabilities and easy recyclability.

Nomenclature

CT	Computed Tomography
GFB	Green Fiber Bottle
LCA	Life Cycle Assessment
MPP	Moulded Paper Products
XCT	X-ray Computed Tomography
μEDM	Micro Electrical Discharge Machining process

MPP, because of their aesthetic limitations, have been limited to the use in egg tray packaging for several years, however the demand is increasing due to their sustainable properties [1]. The sustainability of MPP can be defined in terms of the product life cycle. LCA studies can be used as a tool to understand the environmental impact of such paper products. The product life cycle however range from inception of raw materials (in form of obtaining wood from trees) to end of life of the product when it is disposed in the environment. The wood chips are first converted into fine

pulp. Depending on the application of product, mechanical or chemical pulping processes are implemented. Once the pulp is ready to use, it goes through series of sequential manufacturing steps to give it a shape of a bottle. After post-processing operations, such as coating, labelling etc. the product is ready to be used as an eco-friendly packaging product. Several researchers have carried out LCA studies at each step of the bigger product life cycle. Studies with prime focus on wood are discussed in [3]. LCA studies focussing pulp and paper were carried by [4]–[10] and studies concerning moulded pulp and waste paper are discussed in [11], [12] and [13] respectively.

The work done in this paper envisages the manufacturing process of the GFB. GFB is a paper bottle that can be used as a packaging product, alternative to plastic. It is critical to investigate and to build a robust manufacturing process, as it forms a significant element in the overall product life cycle. A key element in the process is the tool or set of tools used for producing the GFB. The prime focus is to investigate upon relatively high dewatering properties of the tool with different tooling solutions. A thorough analysis of the tools and their importance in determining the sustainability of the GFB is outlined and presented in this work.

2. Sustainable manufacturing of GFB

The manufacturing process can broadly be categorized in three segments (a) Pulp preparation, (b) Manufacturing of the GFB and (c) Post processing operations (such as labelling, coating etc.). Pulp preparation can either be done by chemical pulping process or by mechanical pulping process. From a tooling perspective, mechanical pulping process breaks down the fibers, making them lose their strength. Such fibers can easily be moulded in a bottle shape. Das and Houtman [6] carried out LCA to assess the environment impact of the pulping process. The authors compared mechanical pulp against Kraft pulp (chemical pulp). The study revealed that mechanical pulping process have a greater impact on global warming. Chemical pulping process on the contrary have a large impact on acidification. In other categories, no significant distinction was reported.

What is more interesting for this work is the second phase of the production, which is forming and drying of paper fibers in the shape of a bottle. Irrespective of the type of pulp used for manufacturing, the process always includes a drying step. The drying requires significant consumption of energy. The energy contributes to (a) removing water content from the pulp, thus leaving behind a wet network of fibers, and (b) further drying of the wet network thus removing all the water absorbed by the fibers. Huo and Saito [11] in their LCA studies indicated that the drying process is the main contributor in determining the overall environmental impact of the paper product. An incorrect choice of tool can increase the energy consumption thereby disturbing the overall environmental impact.

Not much investigation has been carried out in the direction of assessing the overall environmental impact of MPP [14]. The tooling process described in the subsequent

sections will lay a strong foundation for LCA consultants and researchers to characterize upon the sustainability in the manufacturing of the GFB.

3. Manufacturing Process

The manufacturing process is a two-staged process; at first, paper pulp is prepared. The next stage is the moulding process. The moulding process is also a two-step process. The first step involves forming of the bottle geometry followed by an inflatable core assisted drying process in the second stage. The forming process is carried out in a forming mould (Fig. 1 (a)). The mould consists of holes drilled on the outer surface with a wired mesh tied on the inner surface. The mould is placed upside down. The pulp is injected in the forming mould at high pressure. At the same time, vacuum suction is provided from the outer surface. This results in draining of all the ‘free water’ in the pulp. The pulp fibers are retained by the wired mesh. In this manner, a wet bottle geometry is obtained.

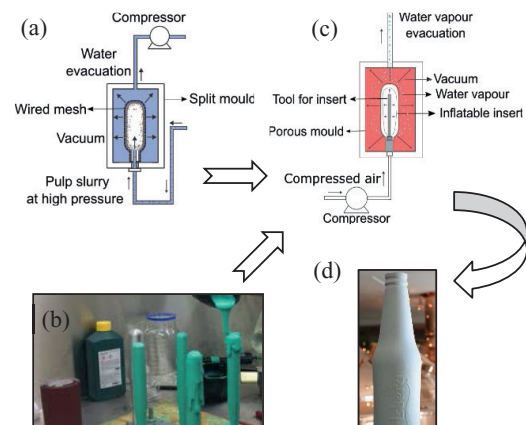


Fig. 1. (a) The forming process; (b) Inflatable core; (c) The drying process and (d) A GFB prototype

The next stage involves removal of the ‘bound water’ content from the paper fibers. In order to remove the water absorbed by the fibers, the formed shape is transferred to the drying mould (Fig. 1 (c)). The drying mould is made of porous tool and preheated to 140°C. The wet bottle is placed inside the drying mould, and an inflatable core, made out of silicone is inserted in the tool (as shown in Fig. 1(b)). The core is inflated inside the tool at high pressure, thus pressing the wet bottle against the porous tool. As soon as the wet bottle comes in contact with the heated tool, the water in liquid phase gets converted to steam. The steam is sucked out, by creating a vacuum suction from outside of the porous tool. The dried bottle (shown in Fig. 1(d)) is then removed from the mould sent for post-processing such as coating and labelling, depending on the usage and application of the bottle.

4. Tool Requirements

In order to develop a robust manufacturing process, it is critical to identify the key requirements for functionality of the tool. The tool must possess the following characteristics:

- Ability to flush out water from the pulp.
- Replicate the tool geometry onto the paper surface.
- Uniform compaction of paper throughout the geometry.
- Non-replication of tool features such as evacuation channels.
- Ability to sustain large number of production cycles.
- Tool material should be corrosion resistant and neutral towards the pulp and water.
- Ability to sustain temperatures above 100°C (up to 200°C, to facilitate the drying process).
- Minimize energy losses during the process.

In order to satisfy the above discussed functional requirements two possible tool alternatives are identified, (a) Porous tool materials and (b) Fabrication of a tool with water evacuation channels. Assessment of alternative porous tool materials for water removal is discussed in section 5. In section 6, surface replication from machined tool is talked about.

5. Flow through porous tool

In this section, capabilities of Industrial XCT are identified to simulate the flow behaviour of sintered porous metals to be used as tool materials. The critical part of using porous materials is the existence of connected pores inside the tool, different connected pores form a continuous channel to flush out water from the tool. However, as the grains are randomly distributed inside the material, it is difficult to quantify the flow phenomenon numerically. In this study, three grades of porous bronze material (referred as grade 8, 12 and 20), and one grade of porous stainless steel are characterized using XCT in order to characterize the effective void fraction and connected channels. Then using the scanned samples of each tool material, flow rate simulations using VGStudio Max 3.0 software (VG) is performed. XCT allows measuring both inner and outer geometry of a component with a non-destructive test. With XCT, testing a volume part of the tool can be characterized on its whole and that is the reason such process was chosen.

To obtain a good resolution from X-ray CT scanning, samples of approximately 3 mm x 3 mm x 3 mm of each material were prepared. The industrial CT scanner XTER XT H 225 ST from Nikon was used. The parameters used for the study were as follows: electron beam potential = 205 kV, electron beam power = 10 W, filter kit for ultrafocus target = Copper, 2.5 mm, projections = 2400, frames per projection = 1. For the scans, a shading correction is created and used on all the tested samples to minimize electromagnetic noise. The specimens were first aligned with the beam gun and then glued to the support. After the initial warm up the part was ready to be scanned. Applying the above settings, the 2D image array was collected. From the CT scan a set of 2D images were obtained. Those correspond to the pictures taken by the sensor while the sample rotates. To reconstruct those 2D images into a 3D body, CT PRO 3D Nikon software was used. An example of 2D image is shown in Fig. 2 (left) while the right image shows the reconstructed volume.

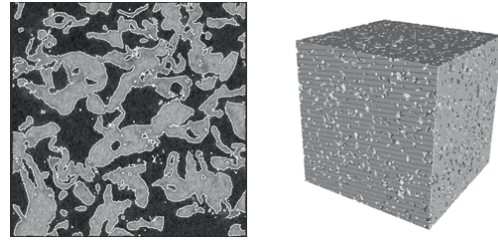


Fig. 2. 2D image (on left) and 3D reconstructed image (on right) obtained from industrial XCT

Once the samples were scanned and reconstructed they were imported to VGStudio MAX software to perform simulations. The faces of the cubes where the difference of pressure is applied are set as the cross section for the simulation as well as shown in Fig. 3.

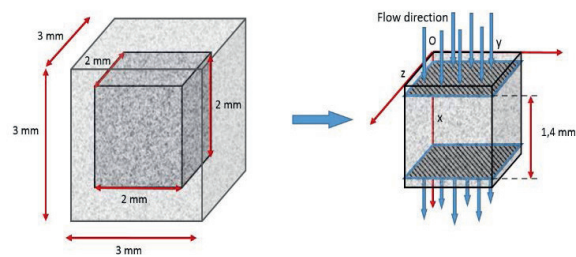


Fig. 3. Volume unit (left) and cross section (on right), used in VG Studio MAX

The mathematical model used by the software uses the Stokes flow, which is a simplification of the stationary Navier-Stokes equation for an incompressible fluid at low Reynolds numbers, i.e., low flow velocity or high viscosity. It assumes that the analyzed fluid is incompressible, laminar flow or it is a one-component flow. The pore space is assumed to be entirely flooded. The Stokes flow can be described with equations (1) and (2).

$$\mu \Delta v - \text{grad } p = 0; \quad (1)$$

$$\text{div } v = 0; \quad (2)$$

Where v is the velocity of the fluid, p is the pressure, μ is the dynamic viscosity of the fluid, Δ is the Laplace operator, grad is the gradient operator, and div is the divergence operator. The value of the absolute permeability is calculated using Darcy's Law for three dimensions in (3)

$$\langle \bar{v} \rangle = \frac{-k}{\mu} \langle \text{grad } p \rangle. \quad (3)$$

Where v and $\text{grad } p$ are the three-dimensional flow velocity and the pressure gradient, respectively, $\langle \cdot \rangle$ denotes volume averaging, and k is the symmetric absolute permeability tensor of rank two.

Following assumptions have been made: (1) Steady-state flow, (2) Laminar flow, (3) Incompressible flow, (4) No heat loss to the surroundings, (5) Water exits at 80°C

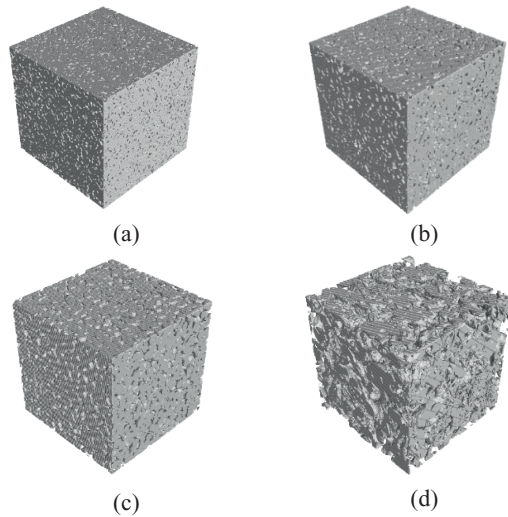


Fig. 4. 3D images of the simulated porous materials (a) Porous bronze grade 8, (b) Porous bronze grade 12, (c) Porous bronze grade 20 and (d) Porous stainless steel

Fig. 4 shows the simulated porous materials. To determine the porosity of material and to identify the existence of connected channels, void fraction parameter is used. The void fraction discussed here, is essentially the percentage of connected channels, accessible for the water transport Fig. 5.

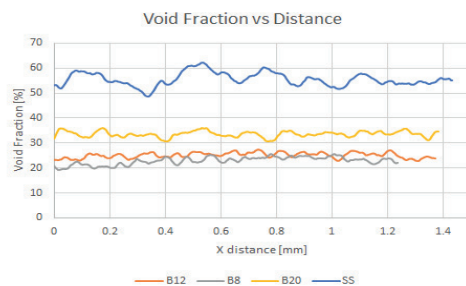


Fig. 5. Void fraction vs thickness in porous materials

Porous stainless steel material shows highest void fraction, over 50% and highly differentiated than bronze samples. The bronze material discs range from 35% to 23% and to 20%, with B20 being the highest, then B12 and B8 the least porous.

6. Surface replication

6.1. Manufacturing of paper discs

In order to have more control on the process and to provide easy access to water flow, the water evacuation channels can be machined using non-conventional manufacturing processes. However, it is important to take into consideration that the features should not be replicated on the paper surface. In order to investigate the feature size, a replication study was carried out. Eight micro features were manufactured on stainless steel material. The feature dimensions were in the order of 35 μm , 50 μm , 75 μm , 100 μm , 200 μm , 300 μm ,

500 μm and 1000 μm hole diameter and the depth in the aspect ratio of 1:2. A master plate was machined with the desired dimensions using μEDM milling. The μEDM milling process makes use of a rotating electrode. The electrode is moved on a three dimensional path, during the movement the material is removed by the continuous discharges. Due to the complexity involved in machining the micro features, the feature sizes were little different from the desired ones. The actual dimensions were as shown in the Table 1.

Table 1. Dimensional features on master plate

S.No.	Hole diameter (μm)	Depth (μm)	Feature number
1.	37	40.28	8
2.	55.2	90.21	7
3.	74	168.87	6
4.	81.7	190.09	4
5.	177	404.52	5
6.	324	452.58	1
7.	516	951.57	2
8.	1009	1908.2	3

A wet paper disc of diameter 100 mm is formed by a 2D disc former. The wet disc is then transferred to the moulding machine shown in Fig. 6. The moulding machine, consists of two moulds. The upper mould is fixed to the outer frame of the entire setup and connected to the resistor heaters, capable of heating up half of the mould to the desired temperature. The mould is designed with a slot spaced in the middle for the interchangeable master plates. The plates are fitted in the slot with a screw. The lower mould is fixed to the double acting piston. It consists of two functional parts, a backing plate and a vacuum plate. The backing plate acts as a flat surface and is used to push the wet disc against the upper mould with insert and to provide orifices allowing the excess water to be removed from the disc. The vacuum plate is connected to the vacuum source.

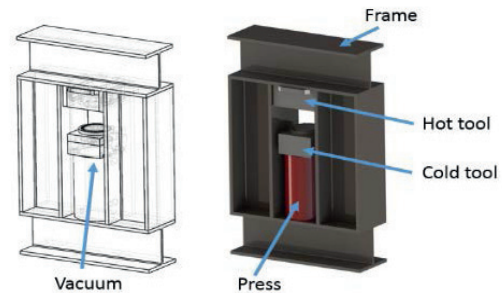


Fig. 6. Experimental setup for manufacturing of paper discs

Following process parameters were set on the machine, Pressure on the mould = 50 bar, Temperature = 170°C, holding time of 5 seconds (without vacuum) and pressing time of 60 seconds (with vacuum), total time = 65 seconds. A replicated disc specimen is shown in Fig. 7.

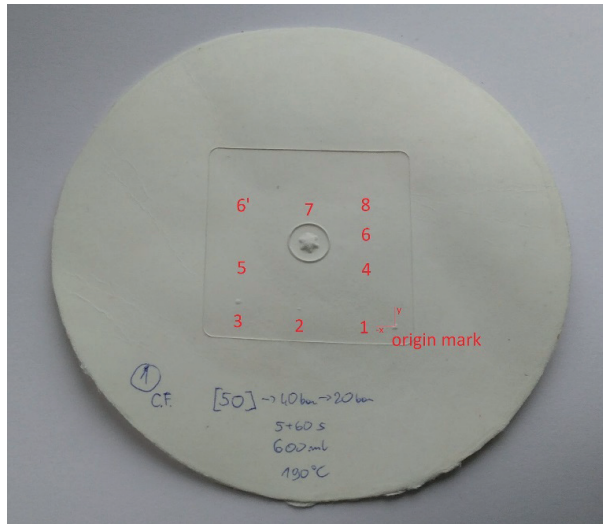


Fig. 7. Replicated paper disc

6.2. Measurements

The visual inspection of the manufactured replications on the paper disc samples showed that the replication of only the three biggest holes (1009 μm , 516 μm and 324 μm) were visible. The hole diameter of 1009 μm and 516 μm left a clear visible mark on the disc surface. The replication of the hole diameter of 324 μm required a closer inspection. All the other features were not visible with the naked eye. Measurements of the smaller images were conducted using confocal microscopy. Due to the curling of paper discs after drying, the discs were stuck with double sided tape on a flat aluminum plate. The acquisitions were post-processed in SPIP software. Before the measurements, a plane correction was applied to remove the potential tilt in the sample. Fig. 8 shows replication of 55.2 μm diameter hole on paper fiber.

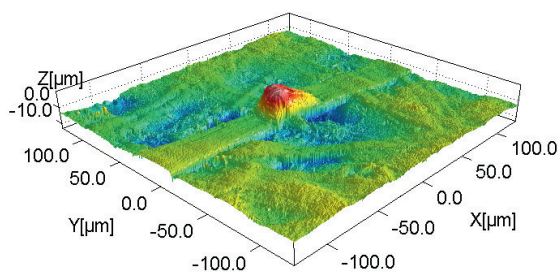


Fig. 8. Replication on single fiber

However, due to the random arrangement of paper fibers, the surface replication can also happen on multiple fibers, as shown in Fig. 9.

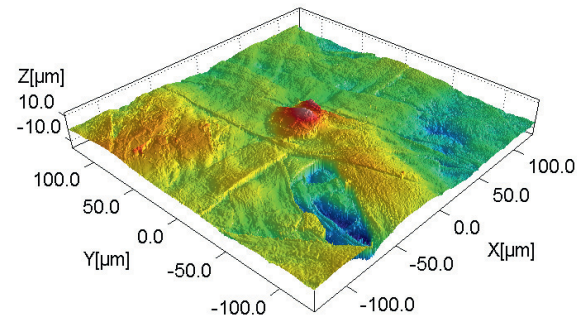


Fig. 9. Replication on multiple fibers.

As indicated in earlier sections, what is more important from tool development point of view is to identify the dimensional limit of features below which the features are not replicated on the paper surface. From this study it is evident, even if the replicated feature can be seen on the microscope, if it is not visible to the naked eye, doesn't interfere with the quality of the produced GFB. The replicated holes turn out to be as pillars on paper surface, the pillars were observed in the hemispherical shape from top. Table 2 summarizes the results from the study.

Table 2. Results of the replication study

S.No.	Hole diameter (μm)	Replicated diameter (μm)	Depth (μm)	Replicated height (μm)	Comments
1.	37	-	40.28	-	No imprint
2.	55.2	51.9	90.21	12.75	
3.	74	73.9	168.87	17.55	
4.	81.7	80.8	190.09	8.95	
5.	177	180.33	404.52	41.02	Poor replication of height
6.	324	330.00	452.58	65.64	
7.	516	522.67	951.57	116.7	
8.	1009	1029.00	1908.2	153.91	

It can be clearly seen from the results that while the diameter is replicated very well for most of the features, the depth is not well replicated. This is because the paper fibers after being pressed at a high pressure, tends to regain their original shape once the pressure is removed. This is also the reason why the horizontal dimension (diameter) is slightly bigger in the replicated surface than the original master plate.

7. Conclusions

The drying process is the main contributor in accessing the overall environmental impact of the GFB. Faster evacuation of water facilitates the drying process. Choice of the right tool can minimize the energy losses during drying. The tool used for manufacturing of the GFB should allow fast removal of water, at the same time maintaining quality of the product. Among porous material, porous stainless steel shows a better

flow rate compared to bronze counterparts. In order to have more control on the process, the evacuation channels can also be fabricated on the tool surface. However, it is important to identify the limit on feature size, which doesn't get replicated onto the paper surface. Feature size of 324 μm and above are visible through naked eye. All the features below this limit can only be seen through microscope. Thus, the quality of the GFB can be maintained by machining channels below 300 μm . It is also significant to examine the water flow rate through these channels, which is not the scope of this study and can be seen as future direction.

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